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An Investigation of Dynamic Subcarrier Allocation in MIMO-OFDMA Systems

Ying Peng, *Member, IEEE*, Simon M. D. Armour, and Joseph P. McGeehan

Abstract—In this paper, orthogonal frequency-division multiple-access (OFDMA) systems with dynamic deterministic (as opposed to pseudorandom) allocation of subcarriers to users to exploit multiuser diversity are investigated. Previously published work on dynamic multiuser subcarrier allocation for OFDMA systems with single-input-single-output (SISO) channels are surveyed. A near-optimal low-complexity algorithm for SISO systems, which is structurally similar to the algorithm by Rhee and Cioffi, is extended to the case of multiple-input-multiple-output (MIMO) systems in this paper. The optimality and adaptability of this algorithm are analyzed by formulating an assignment problem and comparing with one optimal and two extended suboptimal strategies proposed based on previous work. Consideration of a MIMO channel creates further issues for the subcarrier-allocation process. In particular, methods whereby an appropriate subcarrier allocation may be exploited to minimize the effects of correlation in MIMO channels are of considerable interest. Several novel variants of the algorithm (referred to as “schemes”) are proposed and evaluated for MIMO systems employing both space-time block coding (STBC) and spatial multiplexing (SM) in both uncorrelated and correlated fading channels. Simulation results identify the most suitable schemes for both STBC and SM and, in particular, show that substantial improvements in performance (in terms of bit-error rate) in correlated channels can be achieved by means of suitable subcarrier allocation. In uncorrelated channels, the best scheme can offer approximately 7-dB gain over the conventional MIMO channel; in highly correlated channels, even more substantial improvements (> 11-dB gain for STBC, > 20-dB gain for SM) in performance can also be achieved, demonstrating the ability of a well-designed subcarrier-allocation scheme to mitigate the debilitating effects of correlation on MIMO systems.

Index Terms—Multiple input multiple output (MIMO), orthogonal frequency-division multiple access (OFDMA), single input single output (SISO), space-time block coding (STBC), spatial multiplexing (SM), subcarrier allocation.

NOMENCLATURE

$0_{m', N_{\text{Sub}}}$	Matrix of zeros of size m' by N_{Sub} .
$c_{k,n}$	Allocation-mapping matrix element for user k and subcarrier n .
$\tilde{c}_{\tilde{k},n}$	Allocation-mapping matrix element for a user or its duplication \tilde{k} and subcarrier n .

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$C_{k,s,m'}$

\tilde{k}

\tilde{k}

K

\tilde{K}

$h_{k,n}$

$h_{k,n,m'}$

$|h_{k,n}|$

$|h_{k,n,m'}|$

$|h_{\text{user}, \text{sub}}|^2$

H

L

m

m'

M

M'

n

N_{Sub}

N

P_{total}

$P_{\text{total}}^{\text{opt}}$

$P_{\text{total}}^{\text{total}} \times N_{\text{sub}}$

P_{total}

P_{norm}

P_k

q

R_x

s

Matrix to record the location of allocated subcarriers for user k , subcarrier (within the subchannel) s , and spatial channel m' .

User.

User or its duplication.

Number of all users.

Number of S times duplication of K users, $\tilde{K} = S \times K$.

Channel response for user k , subcarrier n for a certain channel.

Channel response for user k , subcarrier n , and channel m' .

Channel transfer-function amplitude.

Relative channel gain in amplitude.

Channel gain of a certain user for the allocated subcarrier in a certain simulation time.

Channel gain matrix, $H = \{|h_{k,n}|^2\}$, $k = 1, 2, \dots, K$, $n = 1, 2, \dots, N_{\text{sub}}$.

Alternative subcarrier in schemes 4 and 5.

Certain spatial subchannel.

Spatial subchannel index $m' = \{1, \dots, M'\}$.

True number of spatial subchannels ($M = T_x \times R_x$).

Effective number of spatial subchannels considered by the allocation algorithm.

Certain subcarrier.

Number of all useable subcarriers.

M' by N_{Sub} matrix, where each row is a vector containing the indexes of the useable subcarriers for the corresponding spatial subchannel (i.e., $N_{m'} = \{1, 2, 3, \dots, N_{\text{Sub}}\}$).

Total perceived channel gain, $P_{\text{total}} = \sum_k^K \sum_n^{N_{\text{sub}}} c_{k,n} |h_{k,n}|^2$.

Maximum total perceived channel gain.

Total perceived channel gain for L times duplication of K users $P_{\text{total}}^{N_{\text{sub}} \times N_{\text{sub}}} = \sum_n^{N_{\text{sub}}} \sum_{k=1}^{N_{\text{sub}}} \tilde{c}_{\tilde{k},n} |\tilde{h}_{\tilde{k},n}|^2$.

Normalized power per user and per subcarrier.

Average received power.

Number of near-adjacent subcarriers avoided in scheme 5 process. The value of ten was chosen on the basis of some crude optimization via a trial-and-error approach and is not necessarily optimal.

Number of receive antennas.

Subcarrier index.

S Number of subcarriers per user in this paper, the case of equal numbers of subcarriers per subchannel, $S = N_{\text{sub}}/K$.

T_x Number of transmit antennas.

I. INTRODUCTION

ORTHOGONAL frequency-division multiple access (OFDMA), which is also referred to as multiuser-OFDM, is an extension of the orthogonal frequency-division multiplexing (OFDM) and is a highly regarded candidate modulation and multiple-access method for a fourth-generation physical layer (4G PHY). It has recently been chosen for the IEEE 802.16 and Digital Video Broadcasting-return channel terrestrial (RCT) standards [4], [5] and received significant research interest. Similarly to OFDMA, various combinations of direct-sequence code-division multiple access [6] and OFDM—e.g., multicarrier code-division multiple-access [7]—are also highly regarded. In practice, there is little difference between the schemes in their robustness against noise and intercell interference [8]. However, OFDMA can often outperform the others for high system loads due to its lower complexity and ability to maintain orthogonality on frequency-selective fading channels.

OFDMA makes use of OFDM modulation while allowing multiple access by separating symbols in frequency and optionally in time as well. In a certain time slot, all or some of the active subcarriers can be used by a given terminal. OFDMA, therefore, concentrates uplink transmit power into a “subchannel,” which consists of $1/N$ th of the whole bandwidth (where N is the number of terminals), resulting in a $10 \log_{10} N$ -dB gain.

Furthermore to this uplink gain, there is also the opportunity to exploit the advantages of multiuser diversity to mitigate channel fading. This is the focus of the algorithms proposed in [1]–[3]. In a frequency-selective channel, subcarriers will perceive a large variation in channel gain, and the perceived channel will be different for each user. If a deterministic rather than random allocation of subcarriers is employed, multiuser diversity can be exploited. In this way, the majority of subcarriers allocated to each user perceive gain (relative to the mean for all frequencies) rather than attenuation in the radio channel. Such a deterministic allocation algorithm will be referred to, here, as a dynamic-subcarrier-allocation (DSA) algorithm.

DSA algorithms have been proposed previously in [1]–[3] for the case where the channel on a per-link basis is single input single output (SISO). Reference [3] is of particular relevance insofar as it is a low-complexity adaptive-multiuser DSA algorithm in which the per-subcarrier channel gain of each user is used as the metric to allocate the subcarriers and ensure a fair allocation for all users insofar as they all receive approximately equal gain from the DSA while not adversely affecting overall system capacity. However, while achieving significant gain, this algorithm might not reach the optimal solution (in terms of achieving the total maximum channel gain for users). The Hungarian method [9] and sort-swap algorithm [10] are introduced and extended to solve this allocation problem as an assignment problem in maximizing total channel

gain and achieve an optimal solution. However, simulation results show that the DSA algorithm in [3] achieves perceived channel gains within a fraction of a decibel of the optimal solution [11].

The core novelty of this paper lies in the fact that it considers another opportunity to exploit diversity in addition to the uplink and multiuser diversity gains described before. This opportunity is specific to multiple-input-multiple-output (MIMO) systems wherein the flexibility of subcarrier allocation facilitates an opportunity to mitigate the debilitating effects of correlation in the channel.

Considering MIMO systems, the DSA algorithm [3] is initially extended to three candidate schemes (schemes 1, 2, and 3)—all MIMO compatible—and performance is evaluated in uncorrelated channels. The schemes inherit the low complexity of the algorithm in SISO and get much benefit from spatial diversity and multiuser diversity in uncorrelated channel scenarios.

However, as is well known, MIMO-system capacity mostly depends on the spatial-correlation properties of the radio channel. An obvious way to achieve decorrelation between a set of antenna elements is to place them far away from each other. However, in most cases, the nature of the equipment will limit the antenna spacing. The nature of the environment may also limit the effectiveness of this method, for example, due to the keyhole effect [12]. Two further adaptive-multiuser subcarrier-allocation algorithms, which are extended from [3] (schemes 4 and 5), are proposed in this paper. These schemes are designed specifically to combat the debilitating effects of correlation while still seeking a maximal or near-maximal allocation of channel energy. The effectiveness of these methods is evaluated in both uncorrelated and correlated channels.

This paper is organized as follows. Section II describes the system model used in this paper. Section III summarizes the DSA algorithm for the SISO-OFDMA system and confirms its near-optimality by analyzing its performance in comparison with optimal and alternative suboptimal solutions. The extended schemes for uncorrelated and correlated scenarios are proposed in Sections IV and V, respectively. Section VI introduces the simulation environment and parameters. Section VII includes all simulation results and performance analysis. Conclusions are provided in Section VIII.

II. SYSTEM MODEL

The OFDMA system considered here consists of one base station (BS) and multiple mobile stations (MSs), all of which possess either two or four antennas. In this paper, the downlink is considered for the sake of simplicity. However, the DSA algorithm and the diversity gains, which it achieves, are, in principle, equally applicable to the uplink (which will enjoy further benefits of OFDMA uplink gain as discussed before). The BS is considered to communicate simultaneously with multiple MSs, each of which is allocated a single subchannel consisting of a given number of OFDMA subcarriers (equal numbers of subcarriers per subchannel and a single subchannel per MS is assumed for simplicity in this paper, but this is not essential to the functionality of the DSA algorithm).

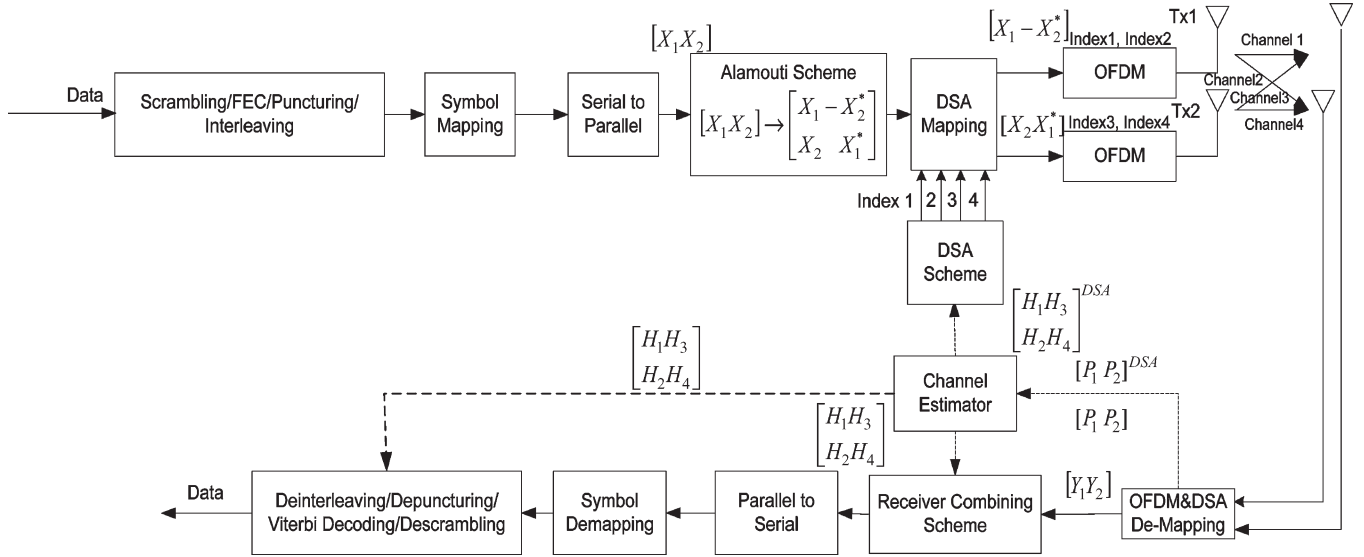


Fig. 1. System model. DSA-OFDMA in SISO system.

The BS takes the downlink data for all MSs and applies independent bit-level-error control coding, symbol mapping, and serial to parallel conversion. In the case of SISO, a DSA-mapping process allocates the parallel data symbols to appropriate subcarriers as indicated by the DSA algorithm. On the other hand, in the case of MIMO, each user signal is subject to either space-time block coding (STBC) or spatial multiplexing (SM) at the BS. The resultant 2 or 4 (depending on the number of transmit elements) coded/multiplexed user-symbol streams are assigned to appropriate subcarriers, as indicated by the DSA algorithm. Subsequently, the symbols are OFDM modulated via inverse fast Fourier transform (FFT), and a guard interval (GI) is inserted between symbols to avoid intersymbol interference. The corresponding block diagrams are shown in Figs. 1 and 2.

The signal received by the MSs takes the form of the BS signal, convolved with the channel transfer-function matrix and additionally subject to additive white Gaussian noise. Symbols sent by the BS to other MSs (users) may be discarded after the FFT in the MS receiver.

After extracting the GI and applying a FFT process at each MS receiver, the subcarriers assigned to a given MSs sub-channel are extracted according to the allocation of subcarriers determined by the DSA algorithm (the method by which this allocation is communicated to the MS is not considered in this paper). Then, for an STBC system, a combining scheme [13] (proposed by Alamouti) is applied. In the SM case, a minimum mean-squared error (MMSE) receiver is used to balance multistream-interference mitigation with noise enhancement and minimize the total error [14]. Finally, the signals, by zero-forcing process (in the case of SISO) or the combined (STBC) or demultiplexed (by MMSE in SM) signals, are subject to forward error correction (FEC). In this paper, convolutional encoding, channel-state information (CSI)-enhanced soft Viterbi decoding, and block interleaving are assumed as a standard case, but the DSA algorithm is, again, independent of such issues.

Three graphs of the system model of SISO and MIMO cases are shown in Figs. 1 and 2(a) and (b) to indicate the whole previously mentioned process. The later two can also be extended to higher dimension MIMO system. Note that all connections to the channel estimator and the control channel between the DSA algorithm and the receiver are shown dashed, since neither channel estimation nor the communication of control information is considered explicitly in this paper. In [15], the impact of nonideal channel estimation is considered in detail in the context of the DSA algorithm, and it is shown that the proposed algorithm is insensitive to channel-estimation errors. The exchange of control information has received fairly limited attention in the open literature [26], [27].

III. DSA IN SISO-OFDMA

The SISO-DSA algorithm presented in [3] is considered as a starting point here. Although structurally similar to the algorithm in [2] (both exhibit relatively low complexity), this algorithm considers the channel gain of each user as the metric to allocate the subcarriers and ensures a “fair” allocation for all users by allocating an equal number of subcarriers to all users. In order to investigate the optimization probability of this algorithm, the classic assignment problem based on channel gain as the metric is first defined and some relative solutions such as an extended Hungarian method, “optimal channel sub-carrier allocation (OCSA),” suboptimal solutions, “maximum gain sort-swap (MGSS),” “DSA” algorithm, and improved “DSA” algorithm “DSA-swap” are presented and compared.

A. Assignment Problem for Optimum Solution

Assuming in an OFDMA system, provision of QoS and data rate requests have been fixed, the number of subcarriers is specified by the request of submitted data rate for each user k . $h_{k,n}$ is the channel response for user k , subcarrier n for a

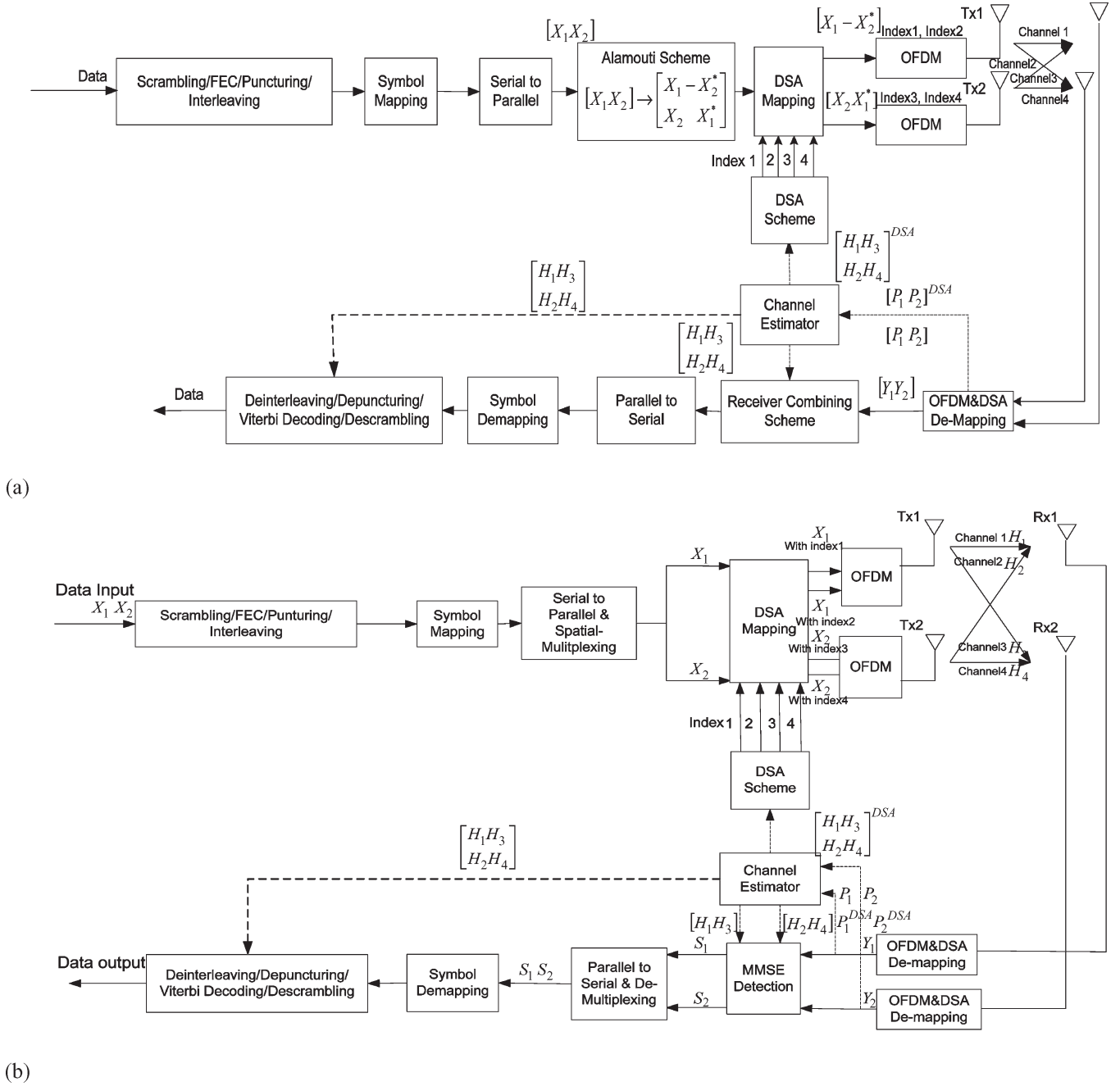


Fig. 2. (a) STBC 2 x 2 OFDMA system model. (b) SM 2 x 2 OFDMA system model.

certain channel. $|h_{k,n}|$ manifests the relative channel transfer-function amplitude. The channel gain matrix $H = \{|h_{k,n}|^2\}$, $k = 1, 2, \dots, K, n = 1, 2, \dots, N_{\text{sub}}$ (K is the number of all users, and N_{sub} is the number of all useable subcarriers) is assumed to be known in the BS for subcarrier allocation. The total perceived channel gain P_{total} for all users is considered in order to provide good subchannels for all users.

Then, the allocation problem can now be formulated as

$$\text{Maximize } P_{\text{total}} = \sum_k^K \sum_n^{N_{\text{sub}}} c_{k,n} |h_{k,n}|^2 \quad (1)$$

subject to

$$c_{k,n} = \begin{cases} 1, & \text{subcarrier } n \text{ is assigned to user } k \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

$$\sum_k c_{k,n} = 1 \quad (3)$$

$$\sum_n c_{k,n} = S \quad (4)$$

where $c_{k,n}$ is the allocation-mapping matrix element for user k and subcarrier n . N_{sub} is the number of useable subcarriers, and K is the number of users (and the number of subchannels as well in this case). S is the number of subcarriers per user.

In this paper (the case of equal numbers of subcarriers per subchannel), $S = N_{\text{sub}}/K$.

The maximum total perceived channel power is indicated by $P_{\text{total}}^{\text{opt}}$.

B. Optimal and Suboptimal Solutions

1) *OCSA—Extended Hungarian Method*: An optimal solution to the above assignment problem can be obtained by an extended Hungarian method. In order to realize OCSA by extending the Hungarian method, the practical problem has to be reformulated. The manipulation of the new matrix $C \in R^{N_{\text{sub}} \times N_{\text{sub}}}$ is considered [16]. The relative gain matrix H should be changed from size of $K \times N_{\text{sub}}$ to $\tilde{K} \times N_{\text{sub}}$, where each user's entry is duplicated for S times (S is the number of subcarriers allocated per user), i.e., $\tilde{K} = S \times K$. Consequently, the size of this new gain matrix becomes $N_{\text{sub}} \times N_{\text{sub}}$ to match the extended Hungarian method.

The optimization problem is reformulated as

$$\text{Maximize } P_{\text{total}}^{N_{\text{sub}} \times N_{\text{sub}}} = \sum_n \sum_{\tilde{k}=1}^{N_{\text{sub}}} c_{\tilde{k},n} |h_{\tilde{k},n}|^2 \quad (5)$$

subject to

$$c_{\tilde{k},n} = \begin{cases} 1, & \text{subcarrier } n \text{ is assigned to} \\ & \text{user } k \text{ at its subcarrier } l \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

$$\sum_{\tilde{k}} c_{\tilde{k},n} = 1 \quad (7)$$

$$\sum_n c_{\tilde{k},n} = 1 \quad (8)$$

where $P_{\text{total}}^{N_{\text{sub}} \times N_{\text{sub}}}$ is the total perceived channel gain for S times duplication of K users, and \tilde{k} is the user or its duplication index $\tilde{k} = 1, 2, \dots, S, S+1, \dots, 2S, \dots, N_{\text{sub}}$. As the allocation-mapping matrix element for this user or its duplication \tilde{k} and subcarrier n , $c_{\tilde{k},n}$ is determined, it can be easily returned to $c_{k,n}$, and $P_{\text{total}}^{\text{opt}}$ can be obtained.

As is well known, the Hungarian method [9] aims to minimize the cost for the assignment problem. The reciprocal of the channel gain can be used to meet this method exactly, but it might reasonably be expected that the optimal allocation cannot be achieved. Hence, it is necessary to invert the method so that the maximum perceived channel gain can be determined.

The subcarrier allocation by the Hungarian method is referred to [9] and [16], in which the assignment problem is the inverse (5) to achieve the minimum cost for assignment of all the jobs among the individuals, such as each individual with exactly one job and each job done by exactly one person. Reference [16] uses a cost matrix of R by R (R is the number of both individuals and jobs) and then searches for the minimum value of the rows and columns by subtracting each element in the rows and columns from the minimum value and minimum lines drawn over all zeros in the processed cost matrix.

In the case of this paper, “job” can be simulated as “subcarrier allocation” and “individual” as “user.” The inversion is a modification of the aforementioned method, following

basic processing rules based on a reformulated channel-gain matrix instead of a cost matrix to achieve the allocation-mapping matrix [9], [16]: 1) Always find the maximum element in each row and column of the channel-gain matrix instead of the minimum element in the cost matrix, and 2) always make locations with their maximum element recorded (such as locating zeros to differentiate other elements).

This is similar to the Hungarian method as a kind of exhaustive search which makes use of computation to check all pairs of “job” and “individual” one by one and compares the total gain for the maximum value. When the size of the channel-gain matrix increases (due to more users and/or subcarriers), the computational time and complexity becomes extremely high. Thus, in this paper, the optimal solution is shown as a reference upper bound of the system performance and is not suggested for use in practice.

2) *MGSS—Suboptimal Solution*: Due to the unfeasible complexity of OCSA, a lower complexity suboptimal solution must be considered. Thus, the algorithm previously proposed in [10] is extended to attempt to achieve maximum perceived channel gain. It is named MGSS and sorts subcarrier pairs by metric of total perceived channel gain and swaps subcarrier allocations between users to exploit the maximum gain. The iteration is applied to make the most of the sort-swap process to achieve a near-optimal solution. In addition, the iterative swap process is used again to improve the DSA algorithm in Section III-D. Note that the channel-gain matrix, which is applied in this solution, is H with original and decreased (relative to OCSA) size of $K \times N_{\text{sub}}$ [the allocation problem is formulated the same as (1)], and the process in [10] is inverted to give the following rules: 1) The elements of initial channel-gain matrix and processed-gain matrix are always sorted in descending order (from highest to lowest), and 2) the subcarriers replacement occurs when the sum of minimum values of all gain-increase-factor per user [10] is negative.

Due to reasonable and low-complexity initial process, the iteration of sort and swap decreases, consequently resulting in the lower complexity and better practicability relative to OCSA.

C. DSA Algorithm

In this section, an algorithmic definition of the proposed (SISO) DSA scheme is provided. The allocation problem is formulated the same as (1)–(4), and in this solution, the channel-gain matrix follows the original size. This algorithm is defined here for the SISO case. The various MIMO schemes are discussed later (and detailed in the Appendices).

In the following, P_k represents the average received power for user k , K is the total number of users, N is an M' by N_{sub} matrix, where each row is a vector containing the indexes of the useable subcarriers for the corresponding spatial subchannel (i.e., the channel that exists between any one transmit element-receive element pair in a MIMO system). The possibility of multiple spatial subchannels is accommodated in the algorithm at this stage (when considering the SISO case) in order to make the algorithmic definition generic to both SISO and MIMO

cases. That is, $N_{m'} = \{1, 2, 3, \dots, N_{\text{Sub}}\}$, where N_{Sub} is the total number of useable subcarriers. $m' = \{1, \dots, M'\}$, where M' is the effective number of spatial subchannels considered by the allocation algorithm. $h_{k,n,m'}$ is the channel response for user k ($|h_{k,n,m'}|$ manifests the relative channel gain in amplitude), with subcarrier n and channel m' . $C_{k,s,m'}$ is a matrix to record the location of allocated subcarriers for user k , subcarrier (within the subchannel) s , and spatial channel m' . $0_{m',N_{\text{Sub}}}$ is a matrix of zeros of size m' by N_{Sub} .

I. Initialization

Set $P_k = 0$ for all users $k = 1, \dots, K$

Set $C_{k,s,m'} = 0$ for all users $k = 1, \dots, K$ and spatial subchannels $m' = \{1, 2, \dots, M'\}$

Set $s = 1$

II. Main process

While $N \neq 0_{m',N_{\text{Sub}}}$

(a) Make a short list according to the users that have less power.¹ Find user k satisfying

$$P_k \leq P_i, \quad \text{for all } i, \quad 1 \leq i \leq k.$$

(b) For the user k obtained in (a), find subcarrier n satisfying

$$|h_{k,n,m'}| \geq |h_{k,j,m'}|, \quad \text{for all } j \in N.$$

(c) Update P_k , N , and $C_{k,s,m'}$ with the n from (b) according to

$$P_k = P_k + \sum_{m=1}^M |h_{k,n,m'}|^2$$

$$N_{m',n} = N_{m',n} - n$$

$$C_{k,s,m'} = n$$

$$s = s + 1.$$

(d) Go to the next user in the short list obtained in (a) until all users are allocated in another subcarrier}.

Thus, the algorithm operates by ranking users in order of current allocated (mean) channel gain from lowest to highest. Subsequently, additional subcarriers are allocated to users in rank order allowing those with the lowest allocated gain to have the next “choice” of subcarrier. The operations in the algorithm, thus, largely consist of sorting, comparing, and performing simple arithmetic.

As well as achieving high multiuser diversity gains (as detailed in the simulation results section), this algorithm has merits in comparison to others including a fair allocation of resources to users and inherent compatibility with link-adaptation schemes.

The algorithm is considered in this paper for the case of ideal CSI. CSI is important, both for DSA and for equalization,

¹For the first iteration (when no subcarriers have been allocated and, hence, all users have equal power). The list may be entirely arbitrary.

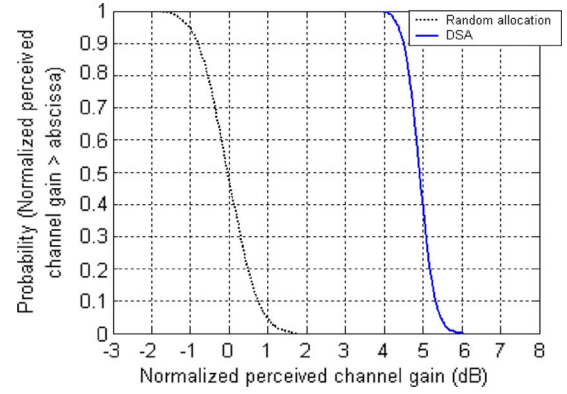


Fig. 3. Comparison of CCDF of total channel gain with conventional OFDMA and DSA solutions.

but the proposed algorithm is relatively insensitive to channel-estimation errors, since only the magnitude of the channel gain is used for the metric to allocate subcarriers [15].

D. DSA-Swap: Improved “DSA” Algorithm

One possible method to improve the DSA algorithm mentioned in Section III-C is to subsequently apply the sort-swap method. The solution of the “DSA” algorithm is used as an initial solution and, subsequently, the swap-iteration process (defined in Section III-B2) can be applied to try to further improve the allocation. The simulation results show that a better performance can be achieved than the initial DSA algorithm solution and that this method can even reach the performance of the optimal solution after enough (about three to five times) iterations.

However, it can be shown in Section III-E that the initial DSA algorithm is a near-optimal solution for achieving maximum perceived channel gain. In the following sections, this algorithm is called directly “DSA algorithm” and extended to MIMO-OFDMA.

E. Comparison of Algorithm Performance

The algorithms described above can be compared via software simulation. In this section, the channel model “E” (defined in Section VI) is used.

In order to simplify (1) and normalize power per user and per subcarrier

$$P_{\text{norm}}(\text{dB}) = 10 \log_{10} \left(\frac{1}{16} \times \frac{1}{48} \times \sum_{\text{user}=1}^{16} \sum_{\text{sub}=1}^{48} |h_{\text{user,sub}}|^2 \right) (\text{dB}) \quad (9)$$

where $|h_{\text{user,sub}}|^2$ is the channel gain of a certain user for the allocated subcarrier (1–48 is the allocated subcarrier index per user and not the index in the real 768 subcarrier sequence) in a certain simulation time.

The total perceived channel gains offered for 16 users by different algorithms are compared. This has been done for 2000 independent identically distributed (i.i.d.) quasi-static random channel instances.

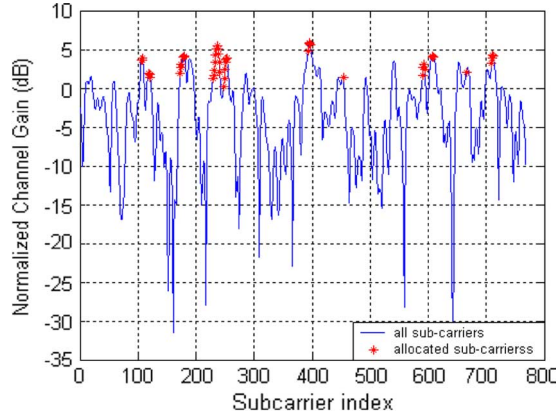


Fig. 4. Example channel response and subcarrier allocation.

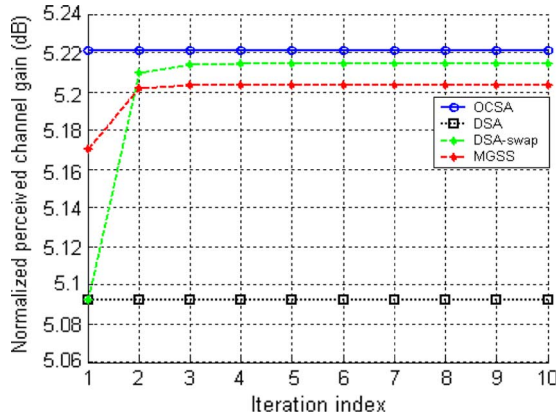


Fig. 5. Comparison of all solutions: OCSA, DSA, DSA-swap, and MGSS.

Complementary cumulative distribution functions (CCDFs) of channel gain achieved by DSA and “conventional” OFDMA (pseudorandom subcarrier allocation) are compared in Fig. 3. It can be seen that DSA outperforms the random-allocation strategy by up to 6 dB and results in significantly lower variation around the mean.

These effects can be justified by considering the example of an instantaneous wideband-channel response in the frequency domain for a single user and the corresponding subcarrier allocation achieved by DSA, as shown in Fig. 4. This serves to illustrate the multiuser diversity benefit, which the DSA algorithm is able to achieve. It can be seen that the subcarriers allocated in this instance have consistently high gain (all are higher than the mean for the channel over all subcarriers) and a much flatter response than the actual channel. These factors lead to the change in channel statistics illustrated in Fig. 3 and the bit-error rate (BER) performance gains demonstrated and discussed in Section VII. It can be intuitively seen how an alternative user perceiving an uncorrelated channel response could derive similar benefit from a different set of subcarriers. It can also be seen that a pseudorandom (or clustered) subcarrier allocation would be unable to achieve this multiuser diversity gain.

The resulting power gains as a function of iteration number is illustrated for one typical channel instance in Fig. 5. Both MGSS and DSA-swap tend to be very close to the optimum solution (achieved by OCSA) after three to five iterations.

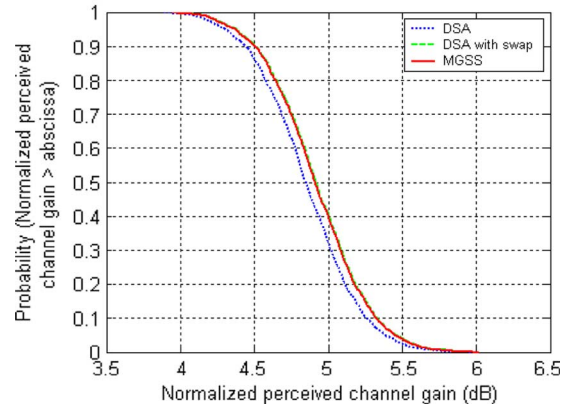


Fig. 6. Comparison of CCDF of total channel gain for all suboptimal solutions.

The result of DSA-swap is slightly better than that of MGSS. Care should be taken to note the scale on the power-gain axis, while DSA and OCSA look far apart on this graph, since DSA actually achieves approximately 97.54% of the power gain of OCSA. Hence, the DSA algorithm (without swapping) can be considered a low-complexity near-optimal solution. MGSS is also worthy of interest because it also offers a low-complexity near-optimal subcarrier allocation. DSA-swap is of less interest, since it offers minimal improvements over DSA and MGSS in return for increased complexity (it is essentially a concatenation of the two).

Fig. 6 presents the CCDF of all 2000 random channels for DSA, DSA-Swap, and MGSS (OCSA cannot be shown because of high complexity in simulation). This shows that the similar performance of these algorithms is consistent across the entire statistical sample.

Having established that all the above algorithms achieve near-optimal performance, the DSA algorithm is identified as the algorithm of primary interest due to one further feature—it is readily extendable to the MIMO case and is particularly amenable to enhancements to combat the debilitating effects of correlation in the radio channel, as discussed in the following sections.

IV. DSA SCHEMES IN MIMO-OFDMA

Three “schemes” to extend the DSA algorithm to MISO (2Tx 1Rx) and MIMO (2Tx 2Rx and 4Tx 4Rx) systems are initially proposed. These schemes are designed to transmit a certain user’s symbols on the subcarriers, which are allocated by the metric from perceived spatial subchannel gain. There is no more than one user per subcarrier per spatial subchannel. Scheme 1 considers subcarrier allocation for each spatial subchannel separately; schemes 2 and 3 allocate subcarriers jointly for all spatial subchannels. These three schemes are extensions of the core algorithm detailed in Section III-C and are detailed in Appendix A.

A. Scheme 1

The DSA algorithm is separately applied for each (spatial) subchannel to determine the subcarrier allocation. This is a straightforward extension of the DSA algorithm, which takes

no account of correlation and no consideration of one spatial subchannel relative to the other spatial subchannels.

B. Scheme 2

This scheme attempts to exploit correlation (primarily to the benefit of STBC systems) by choosing the same subcarrier allocations for all spatial subchannels. This scheme allocates each subcarrier on the basis of the maximum channel gain of all the spatial subchannels for that subcarrier and user.

C. Scheme 3

This is an alternative to scheme 2, which allocates each subcarrier on the basis of the average channel gain of all the spatial subchannels for that subcarrier and user.

D. Comparison of Schemes 1, 2, and 3

Since scheme 1 considers DSA of each spatial subchannel separately (using different sets of subcarriers in spatial subchannels), performance in each spatial subchannel can achieve the same DSA gain as in a SISO system with the DSA algorithm. If spatial channels are uncorrelated, spatial diversity gain is as high as it can be (relative to the equivalent MIMO system in a correlated channel). An increased signal-to-noise ratio (SNR) gain can be achieved because of receiver diversity and more freedom for the BS to allocate available subcarriers.

Schemes 2 and 3 enforce the same subcarrier allocation for all spatial subchannels. The effect of this allocation is similar to that of adding extra multiple components with the same allocated subcarriers by “DSA” algorithm with metric of maximum (scheme 2) or average (scheme 3) channel gain over all spatial subchannels. The system can enjoy both spatial diversity gain and DSA gain as well. This provides for a simpler algorithm and implementation without additional hardware irrespective of the DSA mechanism or channel equalization at the receivers, but it might reasonably be expected that the DSA gain of each spatial subchannel will be reduced.

V. DSA SCHEMES TO COMBAT CHANNEL CORRELATION

As is well known, the spatial-correlation properties of the radio channels are a key to MIMO system capacity. Two adaptive-multuser subcarrier-allocation algorithms extended from the schemes described above are applied to combat the debilitating effects of correlation on a MIMO-OFDMA system. For each user, the subcarrier allocation is performed in a fashion, which reduces correlation while still seeking a near-maximal allocation of channel energy. The details of the processes of these two schemes are described in Appendix B.

A. Scheme 4

As with scheme 1, the DSA is applied independently across spatial subchannels. Additionally, a check is performed to identify cases in which the same subcarrier has already been allocated to the same user in a previously considered spatial

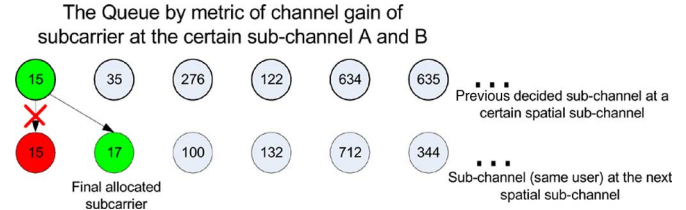


Fig. 7. Example for scheme 4.

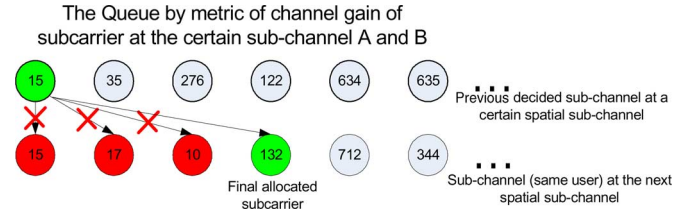


Fig. 8. Example for scheme 5.

subchannel. If this occurs, that subcarrier will be replaced by the next best subcarrier (and the previous allocation check repeated for that subcarrier).

There is an example for scheme 4 (Fig. 7). Provided there are two spatial subchannels A (first row in the figure) and B (second row in the figure), the subcarrier allocation of a certain user (subchannel) has been decided by the DSA algorithm based on channel gain of spatial subchannel A. Currently, subcarriers should be allocated for the same user under spatial subchannel B. The best subcarrier through ranking by metric of channel gain is “15” (the number of a certain subcarrier). However, it can be found that “15” has been already used for the same user in different spatial subchannel. The “15” has been abandoned and the next best subcarrier “17” is chosen by the rules of scheme 4.

B. Scheme 5

In this scheme, not only is the allocation of the same subcarrier to different spatial subchannels prevented, but the allocation of near adjacent subcarriers is also prevented. The number of near adjacent subcarriers avoided in this process is denoted q . It is noteworthy that q may be assumed to take a value of one in scheme 4 and zero in scheme 1, in which case, schemes 1 and 4 may be viewed as subsets of scheme 5.

Similar to scheme 4, there is an example for scheme 5 (Fig. 8). Under subchannel B, not only “15” is abandoned, the “17” and “10” which fall within range of “15” ± 10 (here q is equal to ten) are not allowed for this user. The rule of scheme 5 is forcing the use of subcarrier 132 even though it is three steps further down the ranking list.

C. Comparison Between These Schemes

Since the channel is frequency-continuous, assigning symbols to the adjacent subcarrier locations of an initially chosen subcarrier location should perform similarly (the exception being the case where the coherence bandwidth is not significantly greater than the subcarrier spacing). If the channels are correlated, the adjacent subcarrier locations in other spatial

TABLE I
MODULATION PARAMETERS IN OFDMA

Modulation	QPSK	QPSK	16QAM	16QAM	64-QAM
Coding Rate	1/2	3/4	1/2	3/4	3/4
Data bits per sub-channel	48 (96)	72 (144)	96 (192)	144 (288)	216 (432)
Data bits per OFDM symbol(all 16channels)	768 (1536)	1152 (2304)	1536 (3702)	2304 (4616)	3,456 (6912)
Total Bit Rate [Mbit/s]	64 (128)	96 (192)	128 (256)	192 (384)	288 (576)
Coded bits per sub-channel	96 (192)	96 (192)	192 (384)	192 (384)	288 (576)

subchannels will also be correlated to some extent. Scheme 4 only considers the spatial correlation if the same subcarriers are chosen. Scheme 5 will reduce spatial correlation further but at the expense of some reduction in the DSA gain.

VI. SIMULATION ENVIRONMENT AND PARAMETERS

The performance of the DSA algorithm is evaluated by simulation. The simulation considers mainly QPSK modulated, rate-1/2 convolutionally coded (CSI-soft Viterbi decoded), COFDM operating with a bandwidth of 100 MHz as a candidate 4G PHY. In the SISO-OFDMA case, the simulations at different modulation modes with different convolutional coding rates (Table I) are performed as well for comparison purposes. Note that, in Table I, the values in brackets specify the parameters for SM with two transmitters, and the values not in brackets specify the parameters for the cases of SISO and STBC with two transmitters.

A multipath channel with excess delay of 1600 ns, with each path suffering from independent Rayleigh fading, was used in [17] and [18] for the performance evaluation of similar 4G PHY proposals. On this basis, a similar channel model—referred to as channel “E”—is used here, which is specified by European Telecommunications Standards Institute (ETSI) Broadband Radio Access Network (BRAN) [19]. Channel model “E” corresponds to a picocell-type outdoor environment with nonline-of-sight conditions and large delay spread [20]. The rms delay spread is 250 ns, and the excess delay is 1760 ns with tap spacing of 10 ns.

An addition channel scenario is also considered to investigate the performance in an environment with higher multipath delays. A channel model corresponding to a vehicular microcell environment that was employed in the development of 2G and 3G [21], [22]—referred to here as channel model “V”—is employed. This channel model has an rms delay spread of 370 ns and an excess delay of 2690 ns with the same tap spacing as the channel model E.

The use of both STBC and SM is considered. The 2000 i.i.d. quasi-static random channel samples are used in each simulation, and the subcarrier allocation is updated via the appropriate DSA scheme for each such sample.

It is assumed that the DSA algorithm is implemented by the BS, and that, the BS has perfect knowledge of the channel-gain matrix and uses this to determine subcarrier allocation.

TABLE II
CHANNEL MODEL

Name	‘E’	‘V’
RMS delay spread (ns)	250	370
Excess delay (ns)	1760	2690

TABLE III
CORRELATION SCENARIOS

Correlation Modes	MIMO	
	R_{BS}	R_{MS}
HL	0.91	0.30
HH	0.91	0.91
‘Full’	0.99	0.99

Furthermore, it is assumed that the MSs have perfect knowledge of the channel transfer function for those subcarriers allocated to them and that this is used for equalization and decoding purposes.

For OFDMA and DSA algorithms, 16 users are considered, and there are 768 usable subcarriers in all. Simulation parameters are summarized in Tables I and II.

A. In Uncorrelated MIMO Channels

All three schemes for MIMO are first simulated in uncorrelated channels with results presented in Section VII.

B. Simulations in Correlated MIMO Channels

The simulation is further extended to consider correlated MIMO channels. The derived models are based on [23], which includes the partial correlation between the paths in the channel. Two antennas at the BS and two antennas at the MS are considered. The MS is simulated in an urban environment surrounded by numerous or few local scatters, which results in the lower or higher correlation between two antennas. BS antennas are located on the rooftop level of the surrounding buildings, which follows a Laplacian function in a typical urban environment. The correlation scenarios considered can be seen in Table III. The spatial-correlation matrix of the MIMO radio channel R_{MIMO} is the Kronecker product of the spatial-correlation matrix (R_{BS} , R_{MS}) at the BS and the MS [24], [25]. A selection of results for different correlation scenarios is shown for STBC and SM.

VII. SIMULATION RESULTS

In order to evaluate the proposed algorithm and schemes and compare the performances in different cases, the following simulation results are presented.

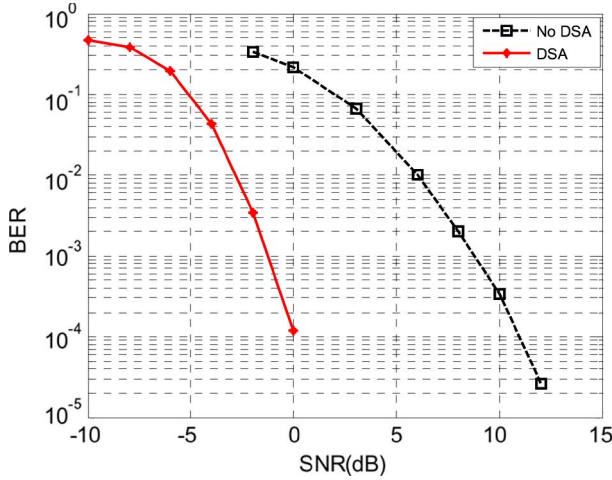


Fig. 9. Average performance of all users in channel “E” (64 Mb/s).

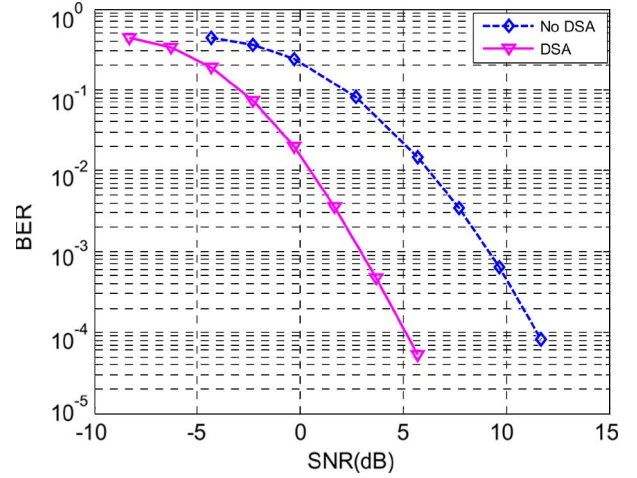


Fig. 11. Average performance of all users in channel “V” (64 Mb/s).

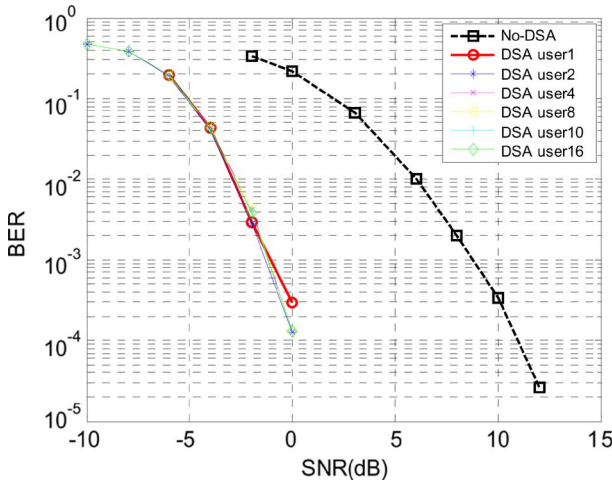


Fig. 10. Performance of a sample of different users in channel “E” (64 Mb/s).

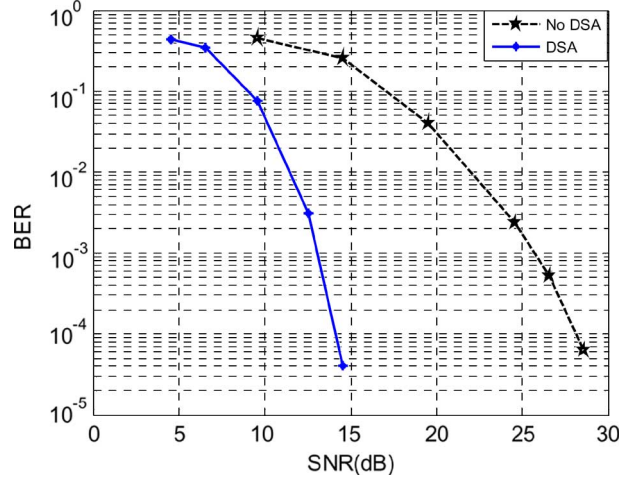


Fig. 12. Average performance of all users in channel “E” (288 Mb/s).

A. DSA Algorithm in SISO-OFDMA

In Section III, it was confirmed that the initial DSA algorithm [3] achieves a near-optimal subcarrier allocation. Thus, in the following, this algorithm is considered in all cases and named directly “DSA algorithm.” In this section, the BER performance is presented for SISO-OFDMA, with and without the DSA algorithm.

Fig. 9 compares the mean performance of all 16 users in channel “E” when operating at 64 Mb/s (1/2-rate QPSK), both with and without DSA. It can be seen that very substantial gains (~ 11 dB at 10^{-4} BER) can be achieved by DSA. While this may seem surprisingly high, it must be considered in the context of the large amount of multiuser diversity gain demonstrated in Section III.

Fig. 10 compares the performance of a sample of different users in the system employing DSA (again, for channel “E” and the 64-Mb/s data rate, the average performance without DSA is shown again for reference). It can be seen that the performance of the users is extremely consistent, there is minimal variation in performance (as a function of received SNR) between users. Only a sample of the 16 users is shown for clarity, but the sam-

ple is a fair representation of the full set of users—performance gains are consistent across all users.

It should be noted that user performance is “equal” on the basis of a comparison of BER against received SNR. Thus, the gain provided to each user by DSA is equal. This does not imply, however, that the performance of all users is truly equal (this is not likely in a real-world environment, where fast fading, shadowing, and free-space attenuation will result in spatially diverse users seeing substantially different radio-propagation conditions), nor that the DSA algorithm acts to compensate disadvantaged users.

Fig. 11 shows the performance gain achieved by DSA in channel “V,” again for the 64-Mb/s data rate. Again, substantial benefits are evident (~ 7 dB at 10^{-4} BER).

Fig. 12 shows the performance gain achieved by DSA in channel “E” for the case of the 288-Mb/s data rate. While the higher modulation order and coding rate naturally results in increased SNR requirements, the gains achieved by the DSA algorithm are actually higher (~ 14 dB at 10^{-4} BER). This can be attributed to the fact that the heavily punctured 3/4-rate code is less able to average errors in the highly frequency-selective

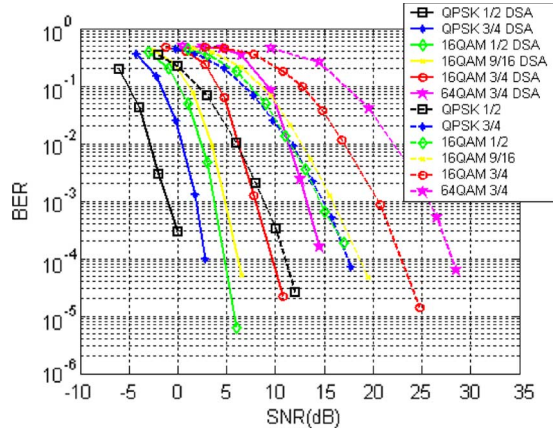


Fig. 13. Performance of a sample of different modulation orders and coding rates in channel "E."

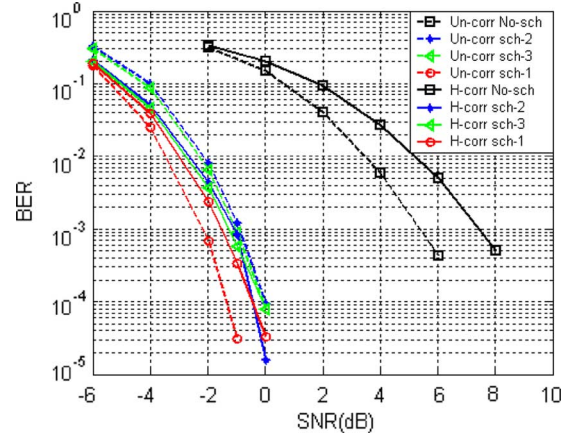


Fig. 15. STBC MISO with correlation mode H.

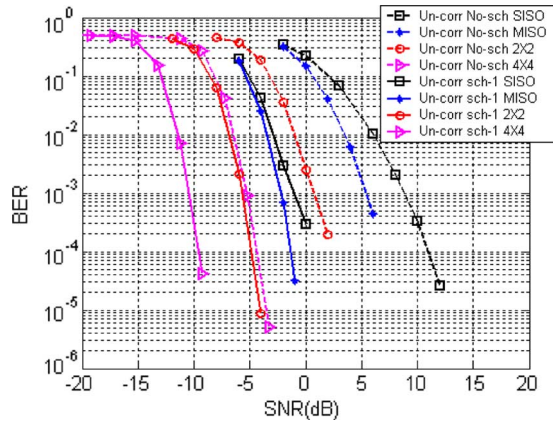


Fig. 14. Uncorrelated SISO and STBC with scheme 1.

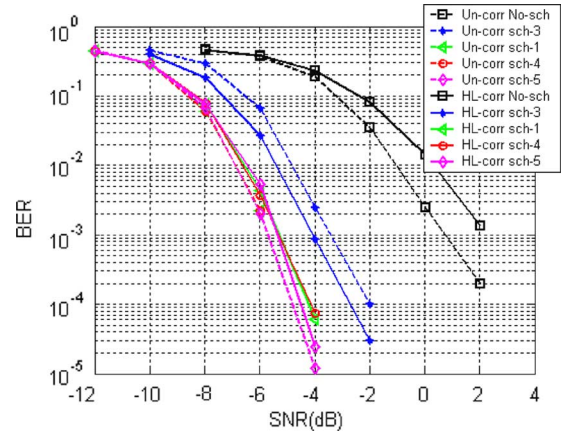


Fig. 16. STBC MIMO with correlation mode HL.

channel perceived by the receiver in the case where DSA is not employed. When DSA is employed, as described above, it has the effect of reducing the variation of the perceived channel in the frequency domain, thereby reducing the requirement for the code to average out fading effects. This implies that DSA has the benefit of facilitating the use of higher rate error-correcting codes. It can be confirmed again in Fig. 13, which lists and compares all modulation orders and coding rates. As an example, there is 6-dB loss from QPSK 1/2 to QPSK 3/4 in the case without DSA but only a 3-dB loss in the case with DSA.

B. Extended DSA Algorithms in a MIMO-OFDMA System

A selection of results is shown as Figs. 14–26. Results cover MIMO-OFDMA systems, both with and without DSA and with either STBC or SM and for various correlation scenarios.

Although scheme 2 has been simulated, results are not shown for all cases. This is because the performance of this scheme is universally similar to, but never better than, scheme 3 (as illustrated in Fig. 15).

Results presented for scheme 5 are for the case where $q = 10$. This value was chosen on the basis of some crude optimization via a trial-and-error approach and is not necessarily optimal.

1) *BER Performance in Uncorrelated MIMO Channels:* All schemes have been simulated in uncorrelated channels, and

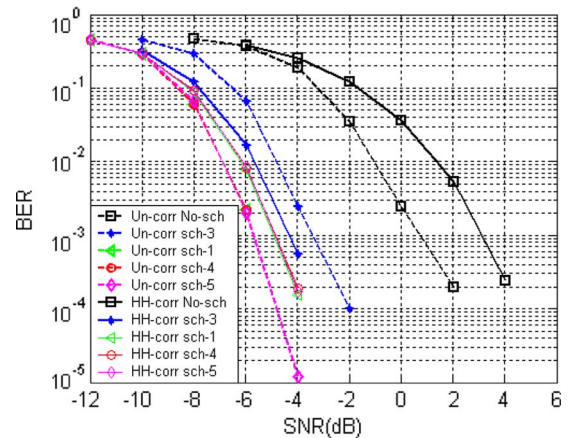


Fig. 17. STBC MIMO with correlation mode HH.

the relevant results are presented for reference in many of the following graphs. In addition, where relevant, for reference, we show the performance of the equivalent system without any DSA applied—"No-Sch."

DSA achieves a gain in the SISO system of more than 10 dB at 10^{-4} BER (Fig. 14). Scheme 1 performs similarly well in uncorrelated channels (Fig. 14), achieving approximately 8-dB gain for STBC MISO, around 6.5-dB gain for STBC MIMO

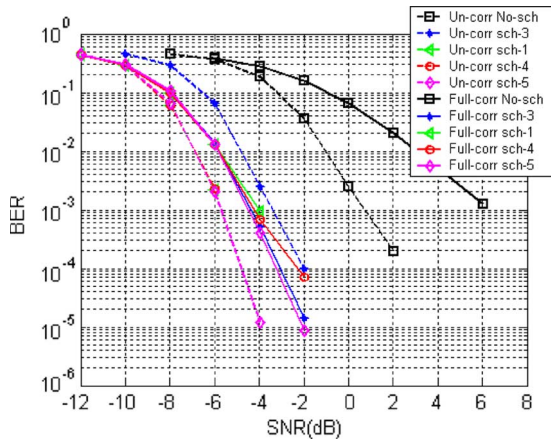


Fig. 18. STBC MIMO with correlation mode "Full."

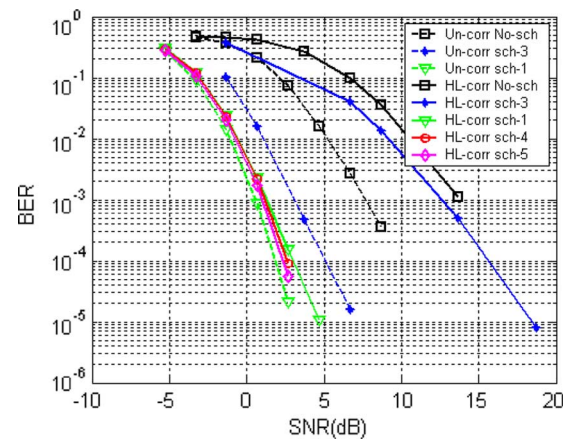
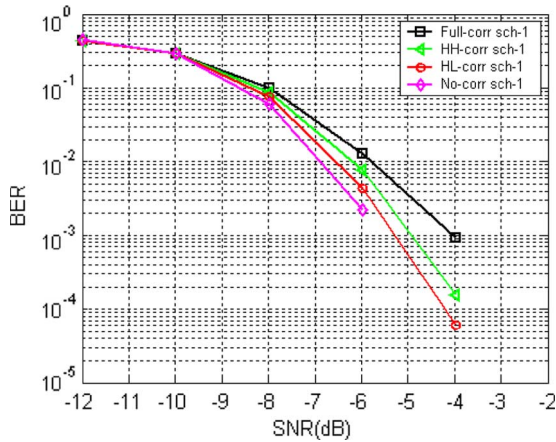

 Fig. 21. SM 2×2 with correlation mode HL.


Fig. 19. STBC MIMO scheme 1.

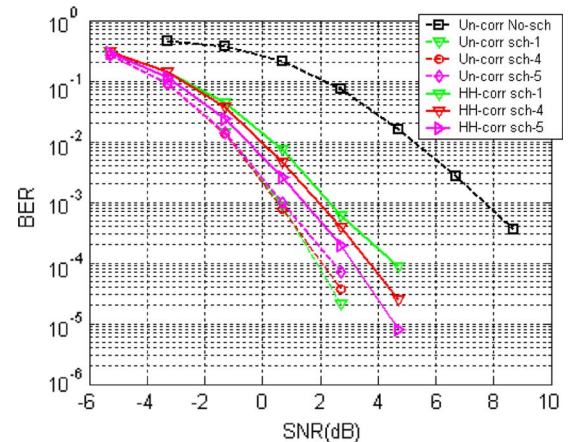
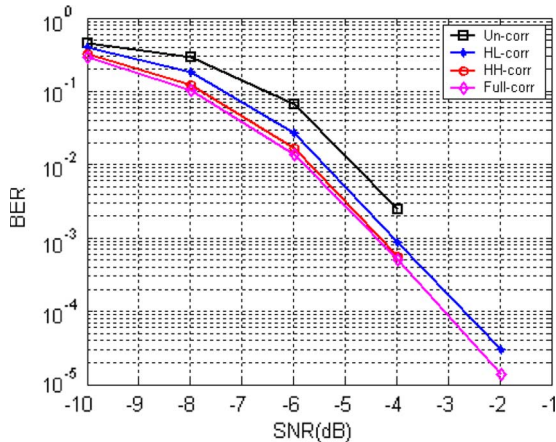
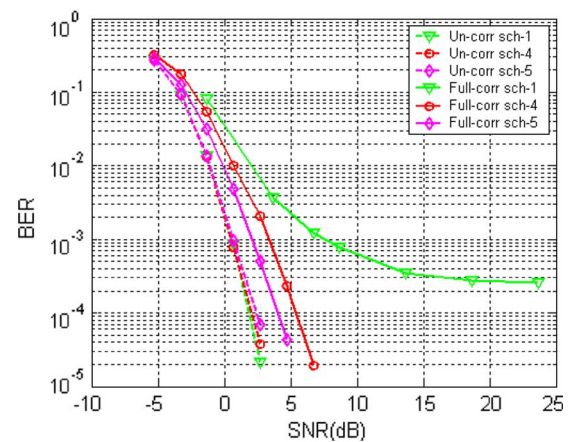

 Fig. 22. SM 2×2 with correlation mode HH.


Fig. 20. STBC MIMO scheme 3.

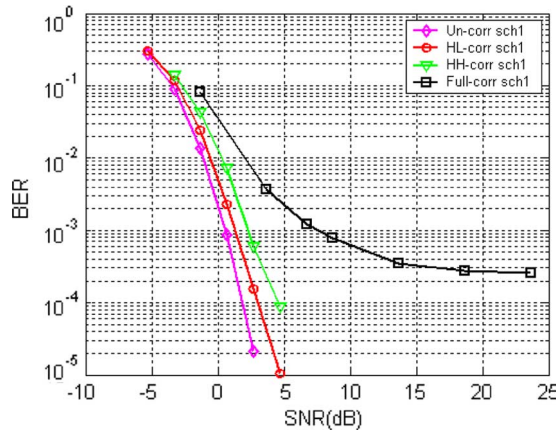
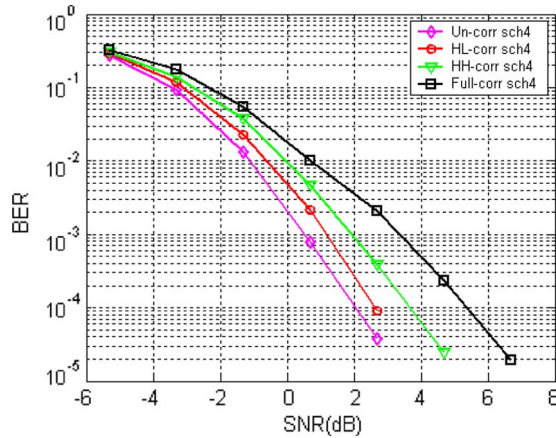
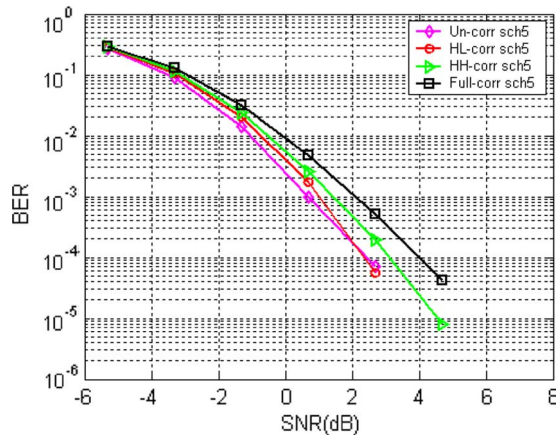

 Fig. 23. SM 2×2 with correlation mode "Full."

(2Tx 2Rx), and 5-dB gain for STBC MIMO (4Tx 4Rx). For simplicity, all following results for STBC MIMO is 2Tx 2Rx. The 8-dB gain is also achieved for SM MIMO (Fig. 21).

It can be seen that, for the case of STBC, schemes 1, 4, and 5 achieve the best BER performance and the (subcarrier allocation) gain closest to that of the SISO system (~ 7 –8 dB according to the uncorrelated curves in Figs. 16–18). The difference in performance between schemes 1, 4, and 5 is

negligibly small. Schemes 1, 4, and 5 always outperform schemes 2 and 3.

For the case of SM, it is shown in Figs. 21–23 that scheme 1 narrowly outperforms scheme 4, which in turn narrowly outperforms scheme 5. This might be intuitively expected since schemes 4 and 5 sacrifice to greater degrees the selection of the best available subcarrier in preference for avoiding allocation of the same or nearby subcarriers on different spatial

Fig. 24. SM 2×2 with scheme 1.Fig. 25. SM 2×2 scheme 4.Fig. 26. SM 2×2 scheme 5.

subchannels. For an uncorrelated channel, such sacrifice achieves no benefit. It is also shown in Fig. 21 that scheme 3 offers the worst performance.

2) *BER Performance in Correlated MIMO Channels:* It is shown that, for correlated channels, in comparison to the results for uncorrelated MIMO channels, scheme 1 is somewhat impaired by the correlation with the degree of impairment increasing with increasing correlation (see Figs. 16–18 and the

summary in Fig. 19 for STBC and Figs. 21–23 and summary in Fig. 24 for SM). It is shown by comparison between Figs. 19 and 24 that (as might reasonably be expected) the impairment due to correlation is much more severe for the case of SM than for STBC.

In comparison, it can be seen (Figs. 16–18 and summarized in Fig. 20) that scheme 3 is actually able to derive some benefit from the correlation when STBC (but not SM) is used. As shown in Fig. 18, however, even for the “full” correlation scenario, scheme 3 only just outperforms schemes 1 and 4 at the upper limit of correlation and still underperforms scheme 5.

As shown in Figs. 21–23, schemes 4 and 5 mitigate the effects of correlation on SM MIMO by different degrees. For HL, HH, and “Full” correlation scenarios, scheme 5 achieves the best BER performance. The degradation in performance of scheme 5 under increasing correlation is shown in Fig. 26 and is relatively graceful. A loss of approximately 1.8 dB is evident between the uncorrelated and “full” correlated cases at a BER of 10^{-4} . Scheme 4 degrades somewhat more severely under increasing correlation, with a loss of 3.2 dB (Fig. 25) at the same BER. As discussed, scheme 1 degrades much more severely than schemes 4 and 5 and is unable to achieve a BER of 10^{-4} in the “full” correlation scenario due to the presence of a distinct error floor (Fig. 24).

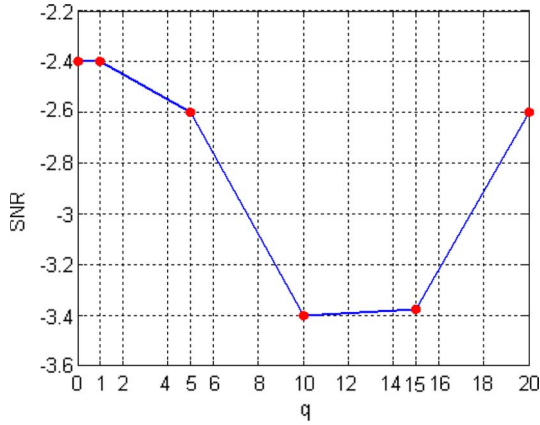
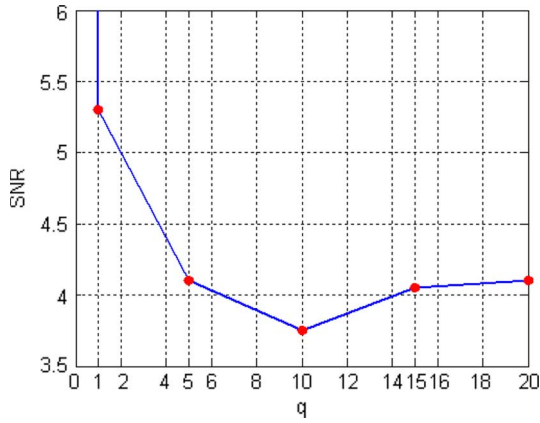
Fig. 23 summarizes the relative performances of schemes 1, 4, and 5 for SM at the extremes of correlation, showing the slight advantages of scheme 1 over scheme 4 and scheme 4 over scheme 5 in uncorrelated channels and the significant advantage of scheme 5 over scheme 4 and a further large advantage of scheme 4 over scheme 1 in the “full” correlated channel.

In addition, with correlation increasing, performance in the absence of any DSA scheme becomes very poor. The benefits of implementing a DSA algorithm, consequently, become greater as correlation increases. The benefits of schemes 4 and 5 over the case without DSA increases from about 8 dB in the uncorrelated channel to more than 11 dB in the “full” correlated channel for STBC and from 14 dB in the uncorrelated channel to more than 20 dB in the HH correlated channel for SM.

3) *Performance Comparison Between STBC and SM:* It is shown that systems employing STBC can survive the effects of correlation better than those employing SM. Schemes 4 and 5 can get slightly better BER performance than scheme 1 for STBC. In highly correlated channels, such as “Full” correlation mode, the performance of scheme 3 is beyond schemes 1 and 4 and very close to scheme 5.

However, an SM system is very sensitive to correlation effects. As the correlation among channels increases to “Full,” the BER performance with scheme 1 comes to an error floor. However, as discussed above, with scheme 5, at a BER of 10^{-4} , there is only a small degradation due to correlation. This result clearly demonstrates the capability of a well-designed subcarrier-allocation algorithm to combat the debilitating effects of channel correlation on MIMO systems.

4) *Comparison in Performances of Scheme 5 With Various q :* The variable q in scheme 5 is investigated. Examples are shown as Figs. 27 and 28. Scheme 4 is also compared as a special case for $q = 1$ and scheme 1 as a special case for $q = 0$. Furthermore, the case $q = 0$ can be considered

Fig. 27. SNR performance for STBC under various q at BER of 10^{-4} .Fig. 28. SNR performance for SM under various q at BER of 10^{-4} .

the optimal value in uncorrelated MIMO-SM systems. Figs. 27 and 28 show the comparison of SNR requirement for the target BER of 10^{-4} as a function of q for both of STBC and SM cases. It can be seen that, in the case of channel “E,” when q increases, less SNR is needed to achieve BER of 10^{-4} until q reaches a value of ten. Values of q larger than ten require more SNR, although not as much as the cases of $q = 0$ and 1. This is because, when q increases, the effect of correlation and loss of spatial diversity can be reduced while the selection of the “best” subcarriers (in terms of channel gain) are sacrificed. As a result, there is a tradeoff between mitigating correlation and achieving DSA gain. For different channel model or correlation modes, the optimal value may change.

VIII. CONCLUSION

In this paper, an algorithm for DSA has been proposed and evaluated in terms of performance in a “4G” mobile broadband WWAN context. The schemes proposed for MIMO systems are the first to consider DSA as a means to combat the debilitating effects of spatial correlation in the wireless channel.

For the SISO case, results show that the DSA algorithm is capable of exploiting the flexibility of fine-granularity frequency allocation facilitated by OFDMA to derive substantial perfor-

mance gains from multiuser diversity. Compared with other heuristic algorithms, this DSA algorithm is identified to be a near-optimal solution to the subcarrier-allocation problem with relative low complexity. Results show that gains vary between 7 and 14 dB, depending upon the channels and modulation and coding schemes considered and that the gains are consistent across users, implying that the algorithm has the additional benefit of achieving a very fair distribution of multiuser-diversity benefits between users. The results for higher data rates also imply that DSA facilitates the use of higher rate FEC codes.

For the MIMO case, considering both uncorrelated and correlated MIMO channels, scheme 5 would appear to be the superior option: Achieving near-optimal performance in the uncorrelated case and providing the greatest degree of robustness to the effects of correlation (less than 2-dB degradation from the full correlated to uncorrelated case). Schemes 1 and 4 (which can be considered to be special cases of scheme 5) cannot reach the best capability to mitigate the debilitating effects of correlation on MIMO systems (scheme 1 even exhibits an error floor); schemes 2 and 3 are less complex and can get benefit from the correlation but generally perform significantly worse than the other schemes.

Scheme 5 achieves this good performance in spite of the fact that the value of q used has not been studied in detail. This is an obvious area for further work and may yield further improvements in performance. Use of an adaptive value for q should be considered as a means of getting the best performance across the full range of correlation scenarios. It can be expected that, as q is changed, the variability of the channel power allocation will be changed. In addition, variation of perceived channel gain will become stronger when q is increased.

The core DSA algorithm and the various MIMO schemes all consists of relatively low-complexity operations (loops, sorting, and comparison). Given the substantial performance benefits that the algorithm has been shown to offer, an attractive cost-benefit tradeoff might be inferred. However, a detailed qualitative analysis of implementation complexity remains an obvious subject for further work.

APPENDIX A

ALGORITHMS OF “SCHEMES” 1–3

A. Scheme 1

This scheme can be defined by nesting the core algorithm (Section III-C) within a loop for all spatial subchannels, i.e.,

For $m = 1$ to M

{As $m \leq T_x$ Perform Core Algorithm;

As $m > T_x$, subcarrier n got in step (b) is checked:

Find s_1, s_2, \dots, s_{m-1} for $C_{k,s_1,1} = n$, $C_{k,s_2,2} = n, \dots$, $C_{k,s_{m-1},m-1} = n$. If two of them are different and s is not equal to any of them, we get the second subcarrier n' satisfying $|h_{k,n,m'}| \geq |h_{k,n',m'}| \geq |h_{k,j,m'}|$ for all $j \in N - \{n\}$ to avoid applying the same subcarrier to more than two allocations. Then, go to (c) with n' instead of n . The rest is same as Core Algorithm.}

where M is the true number of spatial subchannels ($M = T_x \times R_x$, T_x is the number of transmit antennas, R_x is the number of receive antennas). In the process, the constraints of $m \leq T_x$ and $m > T_x$ ensure that each subcarrier is allocated only T_x times, obeying Shannon capacity theorem.

B. Scheme 2

This scheme can be defined by replacing step (b) (the boxed part) of the core algorithm (Section III-C) with this loop process:

{(b)(i) According to k obtained in (a)}

Find subcarrier n_m for all $M = T_x \times R_x$ channels, satisfying

$$|h_{k,n_m,m}| \geq |h_{k,j_m,m}|, \quad \text{for all } j_m \in N.$$

(b)(ii) Find the maximum value among the values obtained in (b)(i)

$$h_{\max_{k,n,m}} = \max(|h_{k,n_m,m}|).$$

Then, go to (c) with n to update P_k , N , and $C_{k,s,m}$. The rest is the same as the Core algorithm.}

C. Scheme 3

Scheme 3 is an alternation of scheme 2. It can be similarly defined by replacing step (b) (the boxed part) of the core algorithm with the following.

(b)(i) According to k obtained in (a)

$$h_{\text{ave}_{k,\tilde{n}}} = \sum_{m=1}^M |h_{k,n_m,m}|, \quad \text{for all } \tilde{n} \in N_m.$$

(b)(ii) For the user k found in (b)(i), find subcarrier n satisfying

$$h_{\text{ave}_{k,n}} \geq h_{\text{ave}_{k,j}}, \quad \text{for all } j \in N_m.$$

The n obtained from above process is brought into (c).

APPENDIX B

ALGORITHMS OF SCHEMES 4 AND 5

A. Scheme 4

As $m = 1$ Perform same as scheme 1

For $m = 2$ to M

{As $m \leq T_x$, go to (*)}

As $m > T_x$, subcarrier n got in step (b) is checked:

Find s_1, s_2, \dots, s_{m-1} for $C_{k,s_1,1} = n$, $C_{k,s_2,2} = n, \dots, C_{k,s_{m-1},m-1} = n$. If two of them are different and s is not equal to any of them, we get the second subcarrier n' satisfying $|h_{k,n,m'}| \geq |h_{k,n',m'}| \geq |h_{k,j,m'}|$ for all $j \in N - \{n\}$ to avoid applying the same subcarrier to more than two allocations.

No matter $m \leq T_x$ or $m > T_x$, process following:

(*) $L = n$ (if $m = T_x$) (or n' if $m > T_x$ and process above) (L is a variable substituted for n)

For $d = 1$ to $m - 1$

{Check whether $L = C_{t,k,1,d}$

If $L = C_{t,k,1,d}$

Find subcarrier \hat{n} satisfying $|h_{k,L,m}| > |h_{k,\hat{n},m}| > |h_{k,j,m}|$ for all $j \in N - \{L\}$

We get the second subcarrier \hat{n} in the average received power list to avoid using the same subcarrier allocation at the same frequency in these channels.

$L = \hat{n}; \}$

Then, go to (c) to update P_k , N , and $C_{k,s,m}$ with L instead of n .}

B. Scheme 5

This algorithm is an extension of scheme 4. The boxed part in scheme 4 has to be changed to

{Check whether $|L - C_{t,k,1,d}| < q$

If $|L - C_{t,k,1,d}| < q$

Find subcarrier \hat{n} satisfying $|h_{k,L,m}| > |h_{k,n',m}| > |h_{k,j,m}|$ for all $j \in N - \{L\}$

We get the subcarrier \hat{n} by order in the average received power list to avoid using the same subcarrier and the adjacent subcarriers at the same frequency in these channels.

$L = \hat{n}; \}$

In this paper, $q = 10$; different value of this parameter can be applied for other cases.

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